

Quark stars: their influence on Astroparticle Physics

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Abstract

We discuss some of the recent developments in the quark star physics along with the consequences of possible hadron to quark phase transition at high density scenario of neutron stars and their implications on the Astroparticle Physics.

1 Introduction

The underlying quark structure of hadrons suggests the possibility of a quark-hadron phase transition at extreme conditions of high temperature and/or density. Since a compact object like neutron star (NS) provide the natural scenario of high density, the suggestion for the existence of quark core inside such massive compact objects was put forward by Ivanenko and Kurdgelaidze (1969). The existence of 3-flavour quark star or strange star (QS), made up of u , d and s quarks, was suggested by Itoh (1970). In general, the two flavour matter can not be more stable compared to nucleonic matter. The presence of s quarks, along with u and d quarks, provides an additional fermi well which would result in the lowering of the energy of the 3- flavour quark matter or strange quark matter (SQM) compared to 2- flavour quark matter. Since s quark has larger mass, the situation would

be more favourable at higher densities. Such possibilities were recognized by Bodmer (1971) and led Witten (1984) to conjecture that SQM may be the true ground state of strongly interacting matter at high densities. Since then, this field has become an active area of research. The possibility of a quark-hadron phase transition in the early universe (high temperature and small chemical potential) scenario and attempts to produce such a matter in the laboratory through heavy ion collision reactions (Alam, Sinha & Raha, 1996) using accelerators have made this field more interesting as well as intriguing.

One of the major difficulty in the theoretical calculations in these areas of research is the fact that the Quantum Chromodynamics (QCD) perturbative series shows poor convergence except for very small coupling at very high temperatures ($\alpha_s < 0.5$, $T \sim 10^5 T_c$). The perturbative treatment at high density also fails. The lattice calculations are still not reliable in the high density regime applicable to NS. Hence the high density systems are studied using the QCD inspired phenomenological models. Numerous model calculations have predicted a stable quark matter system within finite parameter ranges (Ghosh & Sahu, 1993).

Presently, the major technical advancements in both ground as well as satellite based observations are producing huge amount of data. There exist large number of observational data on mass-radii of NS. But, except very soft equations of state (EOS) most of the other EOS can explain these static properties within the error bars (Schaffner-Bielich, 2007). So it is necessary to study different dynamical features of quark matter in its various forms so as to predict unambiguous signatures of QS and validate them using the available observational data.

In this article, we will review the present status of theoretical understandings of the role of quark matter in the development of astroparticle physics, more specifically, the physics of compact objects with quark core (hybrid stars or HS) and QS in the light of various observational studies along with the efforts for the search of strange matter in cosmic rays. We divide the article in few sections. Section 2 deals with symmetry structures of quark matter at high densities. Compact stars' pulsating modes and their importance is discussed in section 3. QCD phase transition and its consequences are discussed in section 4. Section 5 deals with Strangelets. Summary and discussions are given at the end.

2 Symmetries and different quark matter phases

At very high densities and small temperatures, interaction is very weak because of asymptotic freedom. Fermi energy being almost same as chemical potential, adding or subtracting a particle does not cost much. Presence of attractive potential allows the addition of a pair of particles with the attractive channel quantum number resulting into an energetically more favourable configuration. For QCD, the colour coulomb interaction is attractive between quarks having antisymmetric colour wave function. So the pairing in colour space is really a natural consequence of QCD theory itself. Since pair of quarks can not be colour singlet, the cooper pair condensation in colour space will spontaneously break the color symmetry and gluons will acquire mass (Rajagopal & Wilczek, 2000; Alford *et al.*, 2007).

Again since, quarks also have flavour and spin along with colours, there will be many variety of patterns due to quark cooper pairing. For example, with increasing density, fermi surfaces of u , d and s will come closer and one will get first unpaired, then 2-flavour (u & d) paired and finally 3-flavour paired (Colour flavour locked or CFL) quark matter. (Casalbuoni, 2004; Rajagopal & Wilczek, 2000).

Depending on the value of superconducting gap, various form of pairing is expected to occur inside compact stars (Alford *et al.*, 2007) with varied consequences. For example, the cooling rate is given by direct URCA and goes as T^6 for unpaired quark matter, nuclear matter at higher densities and some other forms of matter (Iwamoto, 1982; Ghosh, Phatak & Sahu, 1994, 1996). At very low densities, for proton fraction lower than 0.1, modified URCA is the relevant process and cooling rate varies as T^8 . In case of CFL matter, all the fermions are gapped and the emissivity due to Goldstone modes are suppressed by the Boltzman factor. So the emissivity from CFL matter is governed by the processes involving ϕ , the massless Goldstone boson associated with breaking of $U(1)_B$. Neutrino emission from such processes goes as T^{15} (Jaikumar, Prakash & T. Schäfer, 2002; Reddy, Sadzikowski & Tachibana, 2003). The present observational scenario indicates that some NS cool much faster than others. So, most probably, lighter NS cool following the modified URCA process whereas the heavier NS contain some form of matter, other than CFL, which follows direct URCA process (Alford *et al.*, 2007).

3 Pulsating modes and Gravitation Wave

In rotating neutron stars (RNS), presence of different restoring forces (pressure, gravity, coriolis force etc.) give rise to various modes of oscillations. There are also various damping mechanisms such as viscosity, electromagnetic & gravitational radiation, neutrino emission etc.

In the case of radial oscillation (RO), the star oscillates around its equilibrium configuration maintaining its shape. For non-radial oscillation (NRO), shape of the star is not preserved. The RO may be regarded as a special case of NRO with angular momentum quantum number $l = 0$.

RO in compact stars have been studied by many authors (Benvenuto & Horvath, 1991; Gondek & Jdunik, 1999; Kokkotas & Ruoff, 2001). Different observations, such as radio subpulses of pulsars, short duration spikes in many pulsars and discovery of submillisecond oscillation in celestial X-ray source, have motivated the study of oscillation in compact stars (Boriakoff, 1978; Cordes, 1976; Van-Horn, 1980).

The observation or non-observation of pulsation may also help us to distinguish between the NS and QS. Vath & Chammugam (1992) showed that the periods of RO of QS behave very differently from NS. Instead of having smallest possible period for a given mode, the period of all modes for QS go to zero when the central density of the QS approaches its smallest possible value. Furthermore, bulk viscosity being larger for normal quark matter, RO for QS would damp faster than NS. For CFL QS, damping will be much lesser compared to both NS and normal QS.

Recent studies indicate that the NRO, *i.e.* $l > 0$ oscillations may be more promising compared to the RO for distinguishing between the NSs with different internal composition. This is more so as the RO do not couple to gravitational radiation.

In general, for any star there are two types of NRO, namely spheroidal or polar and toroidal or axial perturbation mode (Kokkotas & Schmidt, 1999). For a Newtonian non-rotating perfect fluid star, all the modes are spheroidal. The axial modes are the trivial modes with zero frequency and without any variation of pressure and density. But for relativistic case, though the picture is otherwise similar, the dynamic space time gives rise to gravitational w- mode. The main characteristics of the w - mode is the rapid damping of the oscillation which increases as the compactness of the star decreases. Moreover, the w- modes do not induce any significant fluid motion (McDermott, Van Horn & Hansen, 1988).

When the star starts rotating, the trivial axial modes become non degenerate and a new family emerges; the r- modes which are analogous to

Rossby waves in earth's ocean. The r- mode pulsation in compact stars are unique in the sense that they are unstable due to the emission of gravitational radiation at all rates of rotation (Andersson & Kokkotas, 2001). The restoring force of these r- modes is the coriolis force and it transfers the star's angular momentum into gravitational radiation. Since several large scale gravitational wave detectors are operational, the study of NRO, especially, r-mode pulsation which are unique characteristics of rotating star, has become important (Andersson, Kokkotas & Sterigioulas, 1999).

For a RNS, there is a critical frequency above which the r-mode instability sets in, angular momentum gets transferred to gravitational wave and star spins down (Andersson & Kokkotas, 2001). This r-mode instability is limited by the viscous damping. For a larger viscosity the critical spin at which r-mode becomes unstable is higher. Since the bulk viscosity of normal SQM is larger than that of normal NS matter, an observation of newly born pulsar spinning near the Keplarian limit would provide the evidence for a QS (Madsen, 2000). Similar situation is expected for 2SC quark star as well. CFL matter has very small shear damping and bulk viscosity. So the heating effect due to the viscous dissipation is less in CFL stars and r-mode damping becomes more important for their evolution. So, except for first few hundred years, CFL stars will cool very slowly and can exist at higher temperatures for many years (Zheng, Yu & Li, 2006).

The unstable r-mode seems to affect the QS differently as compared to NS (Andersson, Jones & Kokkotas, 2002). Unlike NS, the onset of r-mode instability, instead of leading to the thermo-gravitational runaway, results in the evolution of QS to a quasiequilibrium state. Moreover, for QS, r-mode instability never grows to large amplitudes.

The gravitational wave bursts induced by r-mode spin down of HS has also been suggested. The continuous emission of gravitational waves due to r-mode instability from a star can induce a sudden variation in its structure and composition generating further bursts of gravitational waves. This scenario is more probable for HS due to the surface tension between the hadronic and quark matter (Drago, Pagliara & Berezhiani, 2006).

4 QCD Phase transition and Compact Objects

The r-mode instability and the corresponding spin down will cause an increase in the central density of the star. This sudden increase may trigger a phase transition inside the core of NS. In SQM, the strangeness fraction, *i.e.* the ratio of strange quark and baryon number densities, will be unity if one

considers u , d and s masses to be same. Even for relativistic quark masses ($m_s > m_u \sim m_d$), the strangeness fraction at high density is not much smaller than unity. On the contrary, the strangeness fraction in hadronic matter is usually small. Even with hyperons, the strangeness fraction is smaller compared to quark phase. Off course with kaon condensation, the situation may be different. But then, with a kaon condensation inside NS, the transition to quark matter is found to be pushed towards much higher densities (Bhattacharyya *et al.*, 1997). So the transition from hadronic to quark matter may be associated with large strangeness production. Initially hadronic matter that gets deconfined to 2-flavour matter consist predominantly of u & d and some s quark due to the hyperon population. The matter is certainly out of equilibrium. The weak interaction converts this chemically non-equilibrium matter to equilibrated matter with roughly equal number of u , d and s quarks. This conversion is associated with the release of large amount of energy in the form of neutrinos with average energy ~ 100 Mev (Ghosh, Phatak & Sahu, 1996). The total amount of energy released is in agreement with the γ -ray burst energy.

Conversion of neutron matter to SQM may be treated as a two-step process. Deconfinement of nuclear matter, which is predominantly n , p , e^- matter, to u , d and e^- matter takes place in the first step in a strong interaction time scale. The final composition of the 2-flavour quark matter may be determined from the nuclear matter EOS by enforcing the baryon number conservation during the conversion process. This can be studied as the evolution of combustion front moving outward in the radial direction inside the model NS in the special relativistic formalism

In the second step, this 2-flavour quark matter gets converted to SQM. The strange quarks are generated from the excess of down quarks via the non-leptonic and semileptonic weak process, resulting into a charge neutral β equilibrated SQM. Here again, one may assume the existence of a conversion front in the core of the star that propagates radially outward leaving behind the SQM as the combustion product. The time taken to convert the whole star in the above two processes are about 10^{-3} and 100 seconds respectively (Bhattacharyya *et al.*, 2006).

For NS environment, one should really study the conversion along with general relativistic (GR) effect. The GR effect gives rise to different conversion fronts propagating with different velocities along different radial directions (Bhattacharyya *et al.*, 2007a).

Hadronic matter to quark matter phase transition and the resulting neutrino emission can be studied for a RNS. Here, the emission gets predominantly confined to a small angle provided the core of the star is in a mixed

phase and the size of this mixed phase is small. This neutrino beaming may be the missing link that causes the GRB. In general, cross section for the reaction $\nu + \bar{\nu} \rightarrow e^- + e^+$ is very small. The effect of rotation, along with the general relativity, enhances the energy deposition rate substantially and can provide a very efficient engine for the gamma ray bursts (Bhattacharyya *et al.* 2007b).

5 Magnetar and quark stars

The highly periodic pulsation of pulsars are attributed to strong magnetic field ($10^8 - 10^{12}$ G) (Michel, 1982, Lugones, 2005). The study of the role of magnetic field has become more important with the discovery of magnetars. Observed as Soft Gamma Repeaters (SGR) and Anomalous X- ray Pulsars (AXP), these sources are believed to be directly powered by the decay of ultrastrong $\sim 10^{14} - 10^{15}$ G magnetic field and hence are known collectively as magnetars.

There are two reasons which makes QS a possible candidate for magnetar. They are (a) flares with luminosities from some of the SGRs far exceeding the Eddington limit $L_{Edd} \sim 1.5 \times 10^{38} (\frac{M}{M_\odot}) \text{erg/s}$ and (b) the inferred presence of ultra-strong magnetic field.

Case (a) Eddington limit is the critical luminosity of a normal star when the photon radiation pressure from the surface of the star becomes equal to the inward gravitational pressure. As the SQM is bound via strong interaction rather than gravity, QS is not subject to Eddington limit and can radiate at the luminosities greatly exceeding Eddington limit (Usov, 1998, 2001). The giant bursts of SGR0526-66 and SGR1900+14 can be explained in a model where the burst radiation is produced from the bare quark surface of the QS heated by the impact of a massive comet like object (Zhang, Xu, & Qiao 2000).

Case (b) In general for pulsars the loss of rotational energy may account for all the observed radiation. But, for magnetars, the energy emitted in both the quiescent emission (both SGRs and AXPs) and flares (SGR) far exceed the loss in their rotational energy over the same period. The only known source of energy for these emissions is the magnetic energy. The difference between the nature of the normal pulsars and those of SGRs and AXPs raises the possibility that magnetars may have different internal states as compared to ordinary pulsars. One of the possible scenario may be the formation of strongly magnetized core by the strong interaction during the collapse of the progenitor (Soni and Bhattacharya, 2004). Such a

highly magnetized core is possible due to the phase transition from neutron matter to quark matter, neutral pion condensate being the ground state of such matter at 5-6 times nuclear matter densities (Soni & Bhattacharya, 2004; kutschera, Broniowski & Kotlorz, 1990). Such a state carries a large magnetic moment and hence can give rise to a strongly magnetized core.

6 Strangelets and detection : cosmic ray search

While only SQM with very large baryon numbers was initially thought to be favorable (in terms of stability), later calculations have shown (Farhi & Jaffe, 1984; Mustafa & Ansari, 1995,1996) that small lumps of SQM can also be stable. The occurrence of stable (or metastable) lumps of SQM or strangelets would lead to many rich consequences (Madsen, 1999). In general, the stability of strangelets with atomic number A up to 20 - 30 depend rather sensitively on the parameter values (like the Bag constant) and an underlying shell-like structure. For larger strangelets ($A > 40$), the stability appears to be more robust (Madsen, 1994). A discerning property of such strangelets would be an unusual charge to mass ratio ($\frac{Z}{A} \ll 1$) (Banerjee *et al.*, 1999). The obvious place to look for such strangelets would be in the cosmic ray flux.

The detection of strangelet would depend on their mechanism of propagation through the terrestrial atmosphere. It has been shown that a small strangelet with $A \sim 100$ and $Z \sim 2$ can propagate through the atmosphere and reach the mountain altitudes (3-4 Km) with the modified $A \sim 300 - 400$ and $Z \sim 10 - 20$ and a small β (Banerjee *et al.*, 2000a, 2000b).

Several experiments, both ground (Ambrosio, 2000, Balestra, 2006, Cecchini, 2008) and satellite (Madsen, 2005) based, have been designed for the detection of strangelets. Here, one should note that to investigate rare events such as strangelets in cosmic ray, not only a large array of detector is needed, the choice of detector is also extremely important. One of the suitable choice is polymer or plastic detector. But the commonly used plastic detectors such as CR39 and Lexan polycarbonate have detection threshold of $\frac{Z}{\beta} \sim 6 - 10$ and 57 respectively. On the other hand, if the strangelets accumulate large charge during propagation, their $\frac{Z}{\beta}$ would be much larger. In such a situation CR39 like detectors would register a huge low - Z noise which would make the detection of rare events extremely difficult.

In contrast, recently proposed polyethylene terephthalate polymer (PET) or the commonly known Overhead projector (OHP) transparencies (Basu *et al.* 2005, 2008) have been shown to have a much higher threshold $\frac{Z}{\beta} \sim 150$.

A large array of such PET detectors, as planned in Sandakfu, India, would certainly be a very good system for detection of exotic and rare events.

7 summary

QCD transition inside the NSs and possible formation of QSs is one of the most interesting areas of research. We have discussed the different facets of quark star physics along with the associated observational scenarios. Though an observational signature of phase transition and SQM in nature is still elusive, the study of these phenomena is extremely important for a better understanding of the physics of strongly interacting matter. Moreover, there are many questions remain to be answered before we can make any conclusions.

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DISCUSSION

G. BISNOVATYI-KOGAN: For Existence of quark strange stars, their maximal mass should be larger (or not much smaller) than the maximal mass of neutron stars. Can modern theory make reliable estimate of M_{max} for quark stars?

SANJAY K. GHOSH: Quark stars are self-bound, a characteristics of the underlying QCD physics. So, the maximum mass limit estimate for the quark star will carry the uncertainty related to the confinement physics and can be determined only from effective QCD models (Banerjee, Ghosh, Raha 2000).

JIM BEALL: You mentioned that quark stars would be self bound. Does this change the mass limit for these objects?

SANJAY K. GHOSH: Yes. Self bound implies that quark star can be more compact. But then actual estimates will have all the uncertainties of the model parameters. The mass-radius relation of quark star comes out to be very different from neutron stars.

V. CHECHETKIN: Direct numerical calculation of baryon-quark phase transition in neutron star shows that the radius of neutron star decrease by 100 meters only.

SANJAY K. GHOSH: The transition is really a two step process - the process of deconfinement and process of strange quark production along with equilibration. So, it is difficult to do a reliable numerical calculation. Moreover, the result will depend on the how you are incorporating the confinement.

JIM BEALL: Are there radial modes of oscillation that could produce gravity waves?

SANJAY K. GHOSH:No. Radial modes are basically $l = 0$ mode. In dispersion equation l , gets coupled to the gravity part. So putting $l = 0$ decouples the gravitational radiation.

R. BERNABEI: May you comment on the similar searches already carried out and on the improvements of the future ones you are proposing.

SANJAY K. GHOSH:The MACRO as well as SLIM consist of large area passive detectors. So the large area part is certainly not new. On the other hand, strangelets most probably will have high Z/β . So using PET detectors will certainly reduce the large low - Z/β noise.